Enriched Xenon Observatory
for double beta decay

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EXO will be large real time active source search for $\beta\beta$ decay of ^{136}Xe, using isotopically enriched Xenon.

Scientific goals are:

1) Measurement of yet unobserved $\beta\beta2\nu$ decay of ^{136}Xe. Task: $T_{1/2} > 10^{22}$ y. Particularly long.

2) Test of the Heidelberg evidence for $\beta\beta0\nu$ decay. Expectation for ^{136}Xe [Ge $\pm3\sigma$ range $(0.7\text{-}4.2)\cdot10^{25}$ y]:

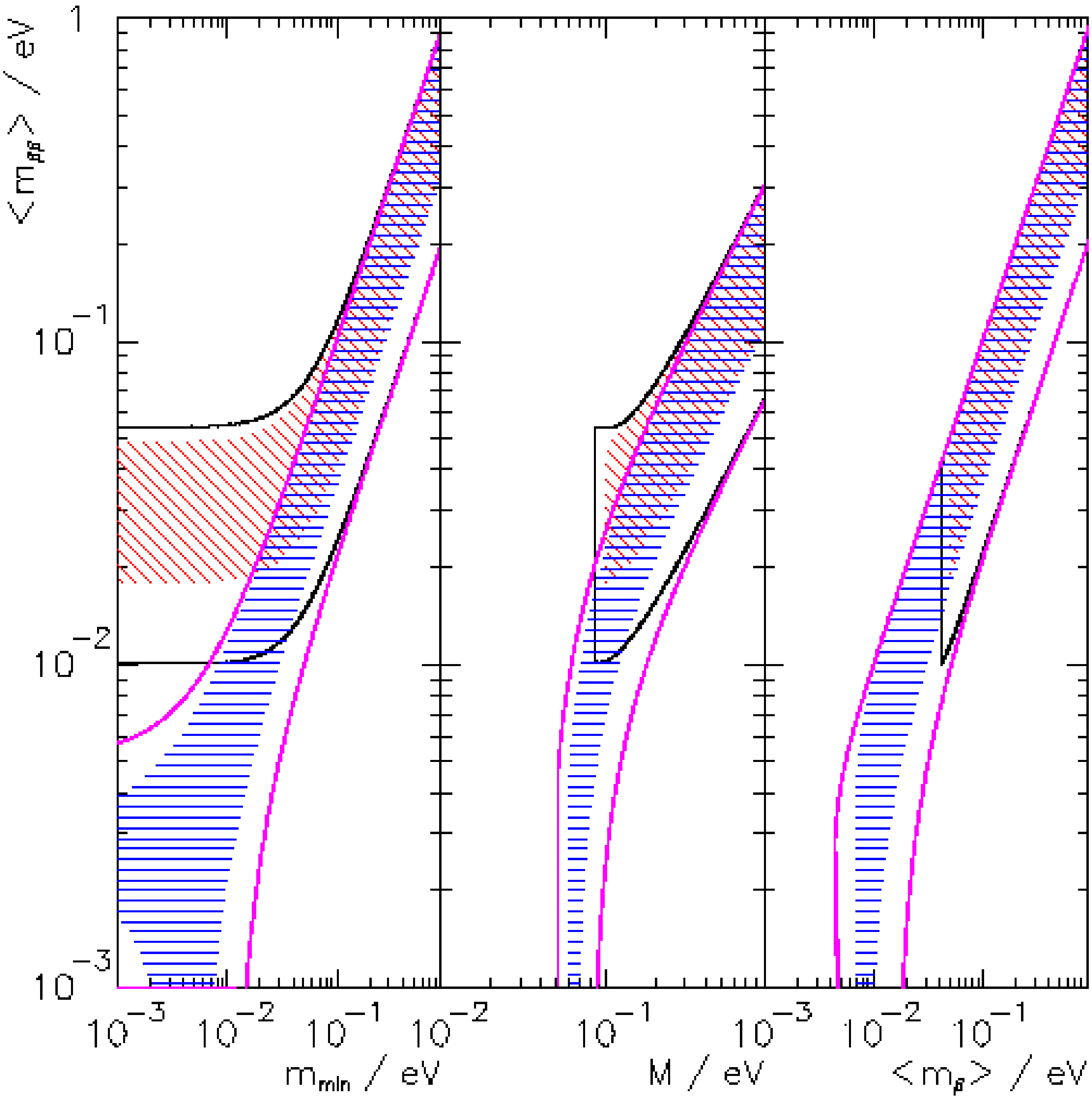
$T_{1/2} = (0.57–3.4)\cdot10^{25}$ y [Rodin et al. PRC68 (2003) 044302 QRPA]

$= (0.66–4.0)\cdot10^{25}$ y [Staudt et al. EPL13 (1990) 31 QRPA]

$= (0.48–2.9)\cdot10^{25}$ y [Caurier et al. NPA654 (1999) 973c SM]

3) Perform a search for $\beta\beta0\nu$ decay sensitive enough to cover the allowed parameter space for an inverted mass hierarchy. $\langle m_{\beta\beta}\rangle < 10$ meV $\rightarrow T_{1/2} > 4\cdot10^{28}$ y [Rodin]

If (2) turns out a negative result.



$\langle m_{\beta\beta} \rangle$ / eV
1
10^{-1}
10^{-2}
10^{-3}
10^{-3} 10^{-2} 10^{-1}
m_{min} / eV
10^{-2} 10^{-1}
M / eV
10^{-3} 10^{-2} 10^{-1}
$\langle m_{\beta} \rangle$ / eV

EXO has chosen ^{136}Xe:

- High Q-value: 2481 keV
- Active detection medium suited for charge collection plus high yield UV scintillator
- No need to grow crystals
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify re-purify during operation
- ^{136}Xe has reasonable natural abundance: 8.9%
- ^{136}Xe advantages for enrichment:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
- Ionization potentials Xe: 12.130 eV, Ba^{+}: 5.212 eV, Ba^{++}: 10.004 eV → ββ–decay product atom remains charged → opens possibility of final state tagging

Major challenges in 0νββ decay

1) Very large fiducial mass (tons)

need large-scale isotopic enrichment

2) Reduce and control backgrounds in qualitatively new ways

unlikely to gain big factors without new techniques

For a background scaling like *Nt*

$$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$$

See M.Moe PRC44 (1991) 931

For no background

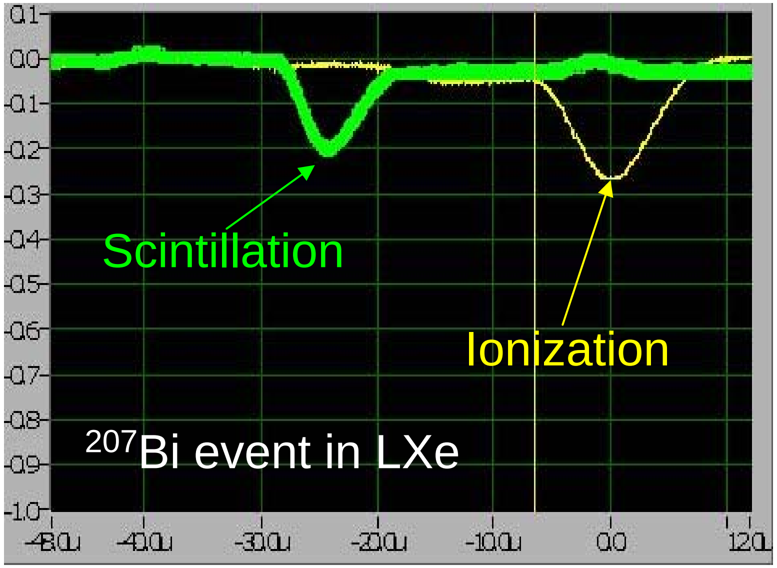
$$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$$

EXO plans to tag Ba^{++} ions born in ββ decays at vertex to operate in this regime.

Challenge: Background Control

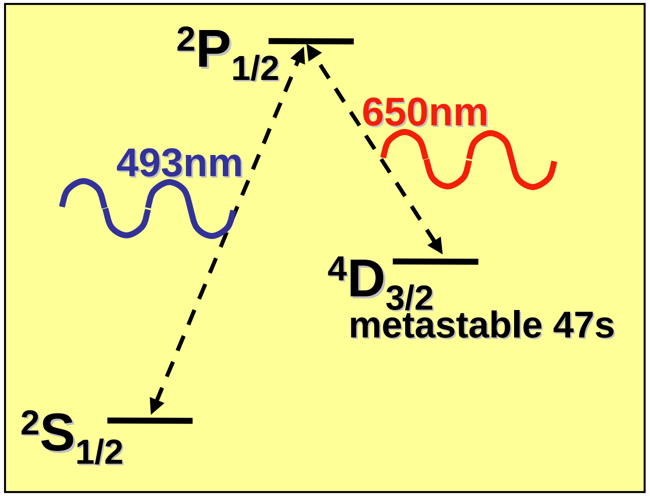
“Real time” (Ionization and scintillation)

+ Energy/tracking information
- γ backrounds
- Isotopic enrichment (usu.)
- Exposure (*Nt*) limited by time



Final state ID

+ Very specific signature
+ Large fiducial masses
- No decay-mode distinction



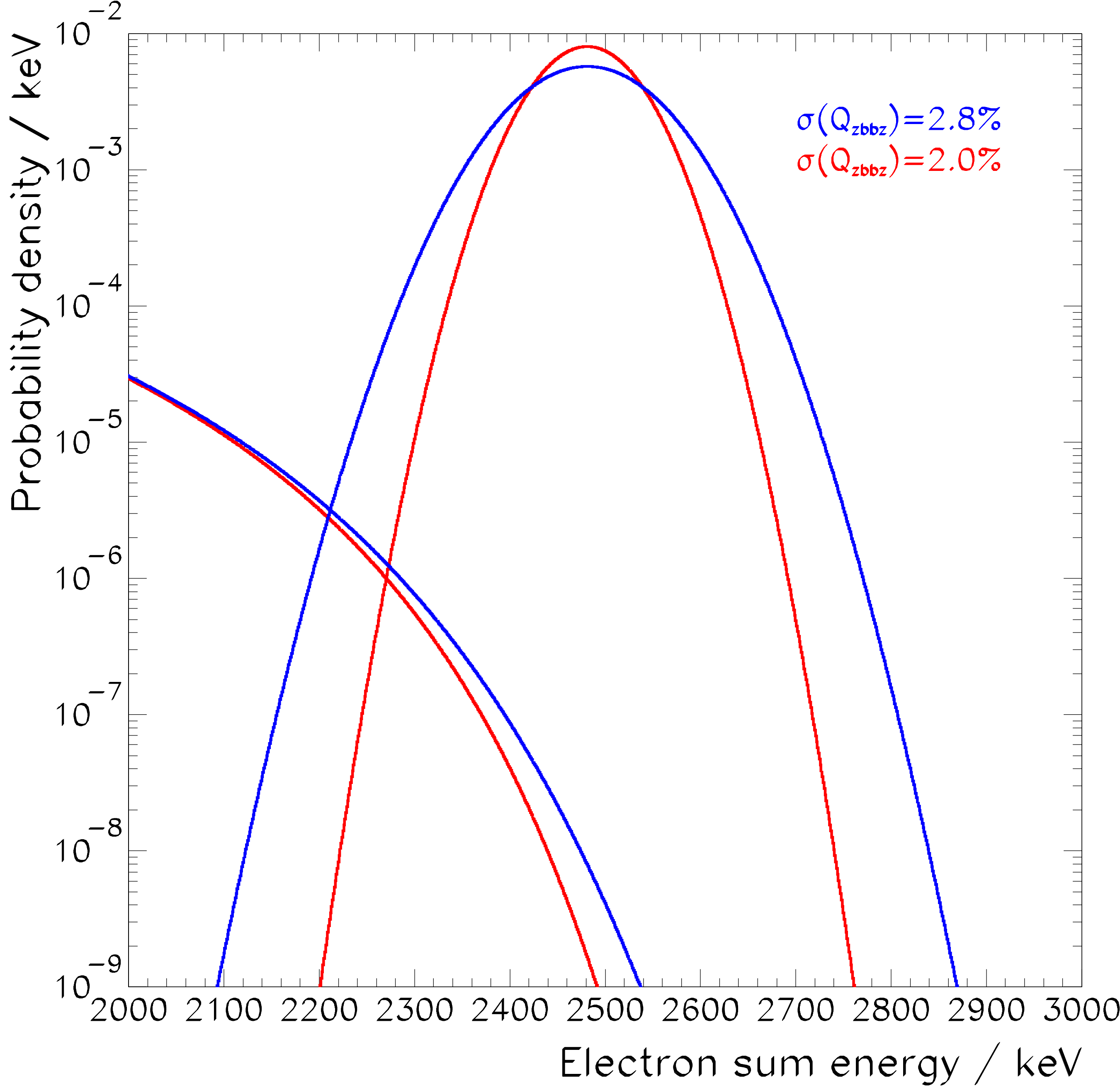
See M.Moe PRC44 (1991) 931

EXO is designed to combine these two techniques

Leakage of ββ2ν-events into ββ0ν-analysis window.

Depends in 5.8th power on σ.

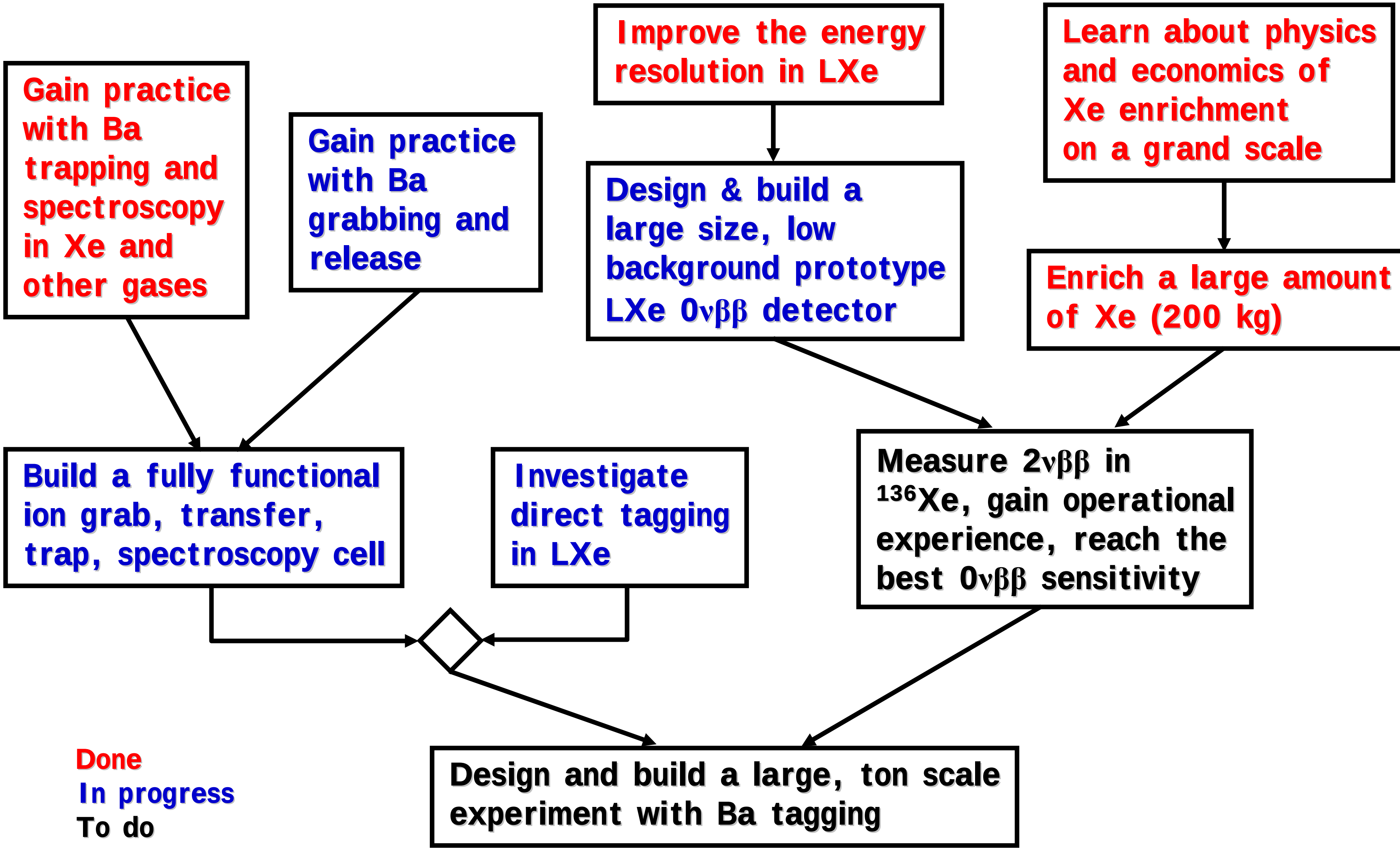
Even with Ba tagging important background.



EXO road map

- Build a 200 kg liquid Xe tracking TPC to demonstrate E resolution, low background, and tracking.
  - Largest liquid Xe detector ever build
  - One of largest TPCs
  - Largest $\beta\beta$ experiment by factor 20 compared to HD-MO
- EXO-200 will initially not be equipped with Ba tagging.
- Will be operated at moderate overburden at WIPP [1585 mw.e. $4.8\cdot10^{-7}$ $\mu/(cm^2\ s)$ Esch et al. astro-ph/0408486] to measure $\beta\beta2\nu$ decay and test Heidelberg $\beta\beta0\nu$ evidence
- Planned installation at WIPP: end of 2006
- In parallel develop Ba final state tagging
- After proof of feasibility build a 1 to 10 ton enriched Xe detector to probe inverted mass hierarchy

The roadmap to the background free discovery of Majorana neutrinos and the neutrino mass scale



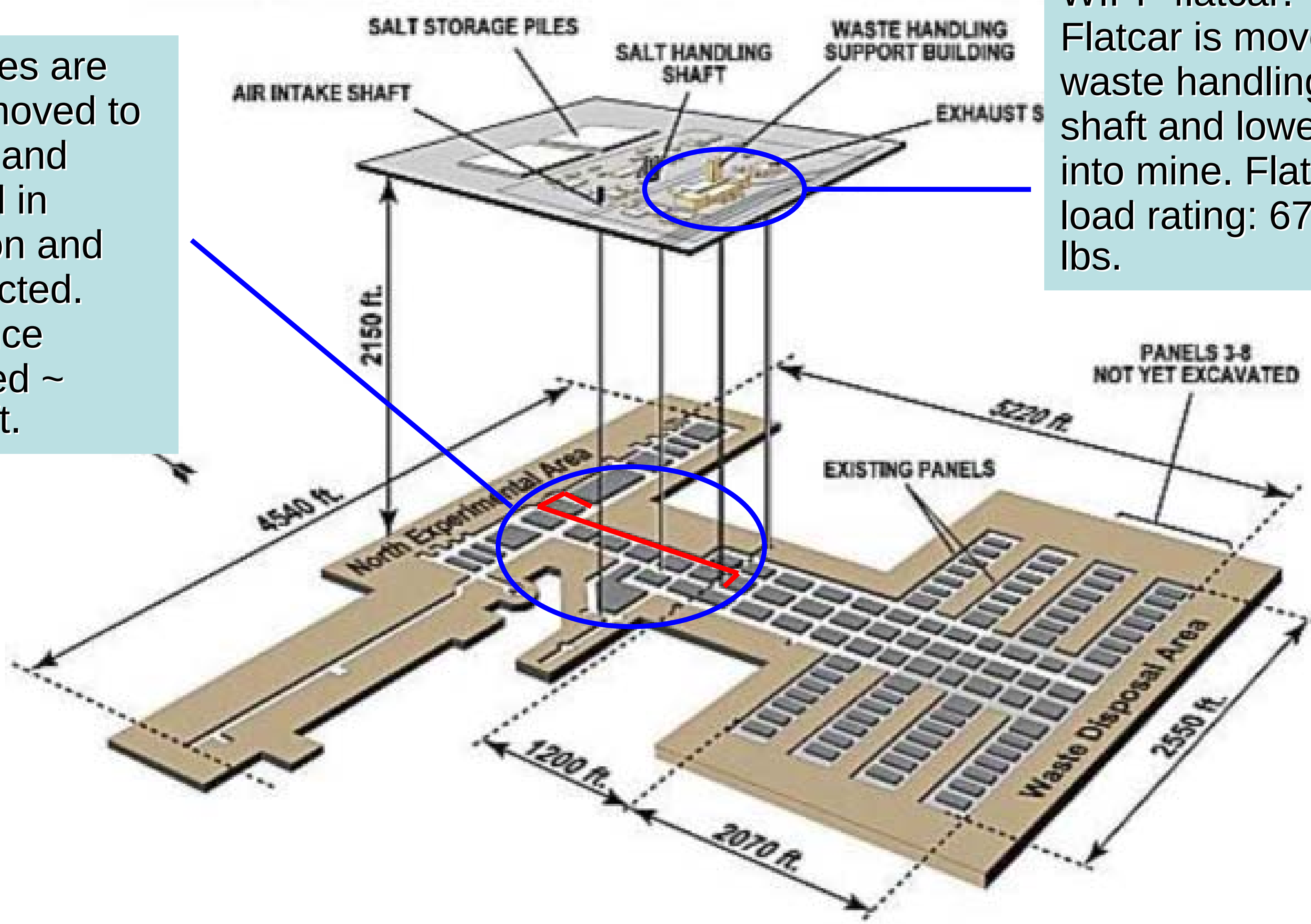
Done
In progress
To do

EXO-200 Progress

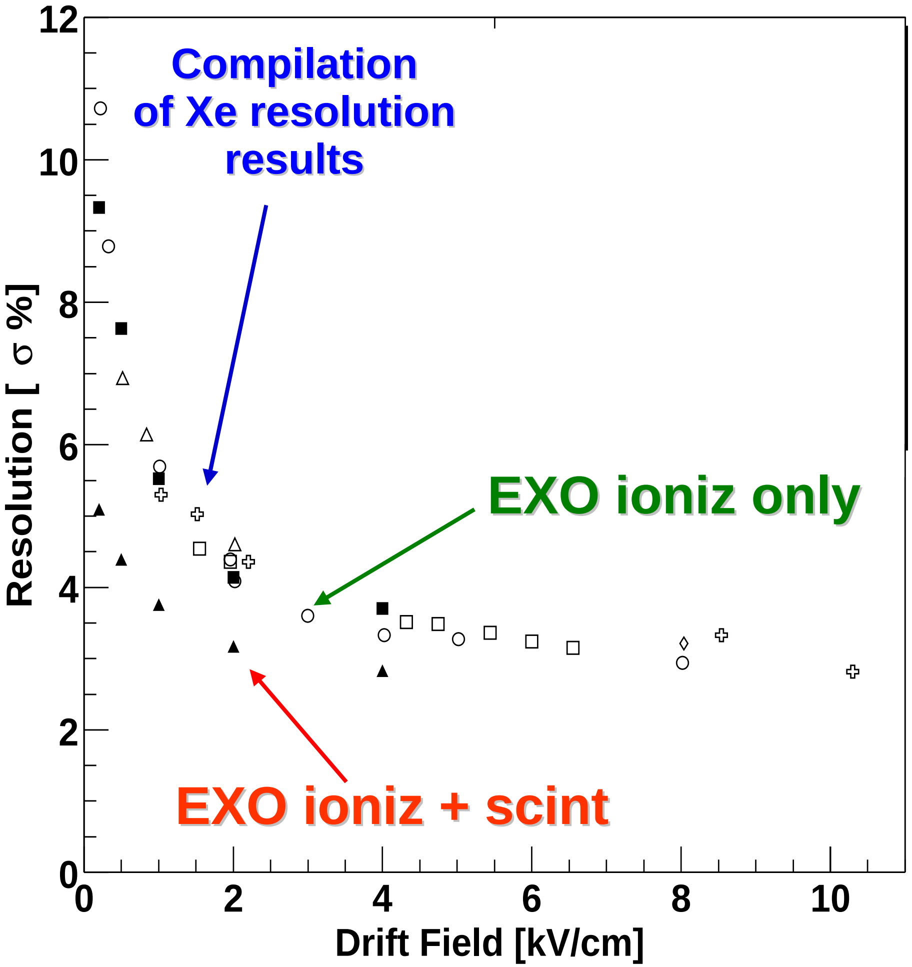
EXO-200 at WIPP

Modules arrive here and are transferred to WIPP flatcar. Flatcar is moved to waste handling shaft and lowered into mine. Flatcar load rating: 67,000 lbs.

Modules are then moved to NExA and placed in position and connected. Distance traveled ~ 2100 ft.



Energy resolution improvement in LXe



Ionization alone:
$\sigma(E)/E$ = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

Ionization & Scintillation:
$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$
(a factor of 2 better than the Gotthard TPC)

E.Conti et al. Phys. Rev. B (68) 054201

EXO-200 will collect 3-4 times as much scintillation… further improvement possible

Massive effort on material radioactivity qualification

- **NAA**[a]
- **Low background γ-spectroscopy**[b]
- **α-counting**[c]
- **Radon counting**[d]
- **High performance GD-MS and ICP-MS**[e]

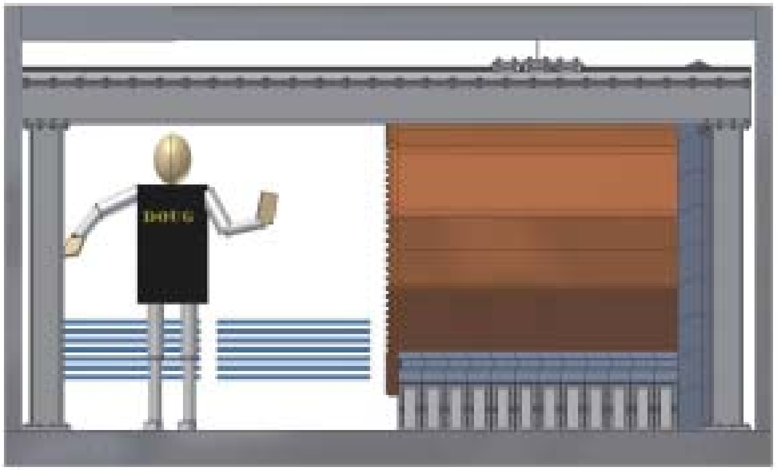
Th/U Sensitivity for Teflon (TPC body): <0.3 ppt or 1 and 4 μBq/kg

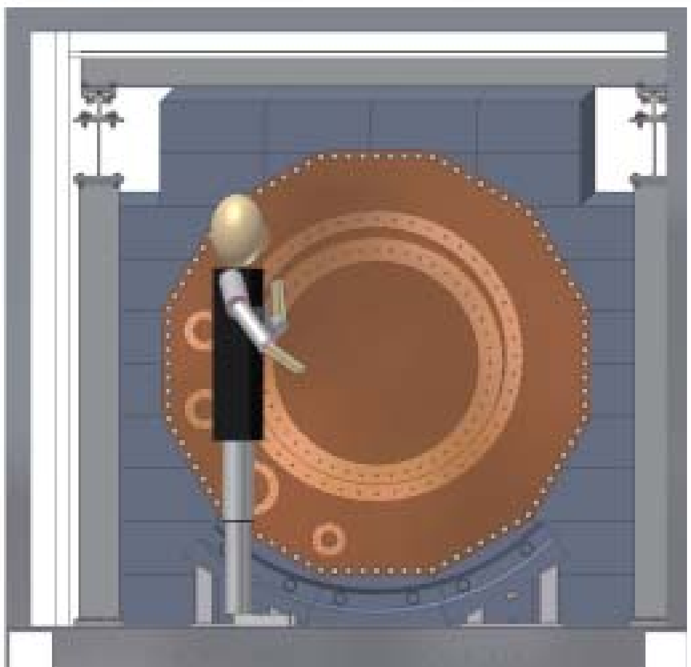
Online database for collaborators at present includes ~130 entries

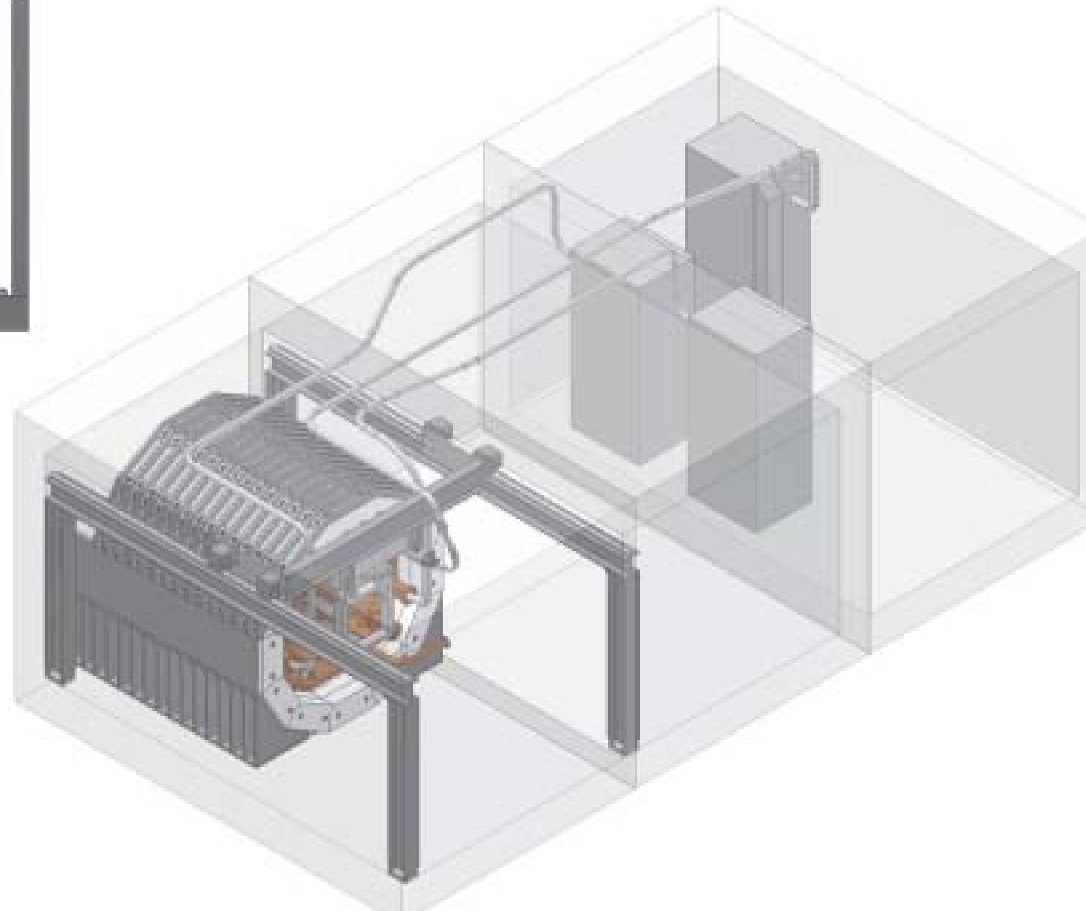
MC simulation of backgrounds Alabama & SLAC

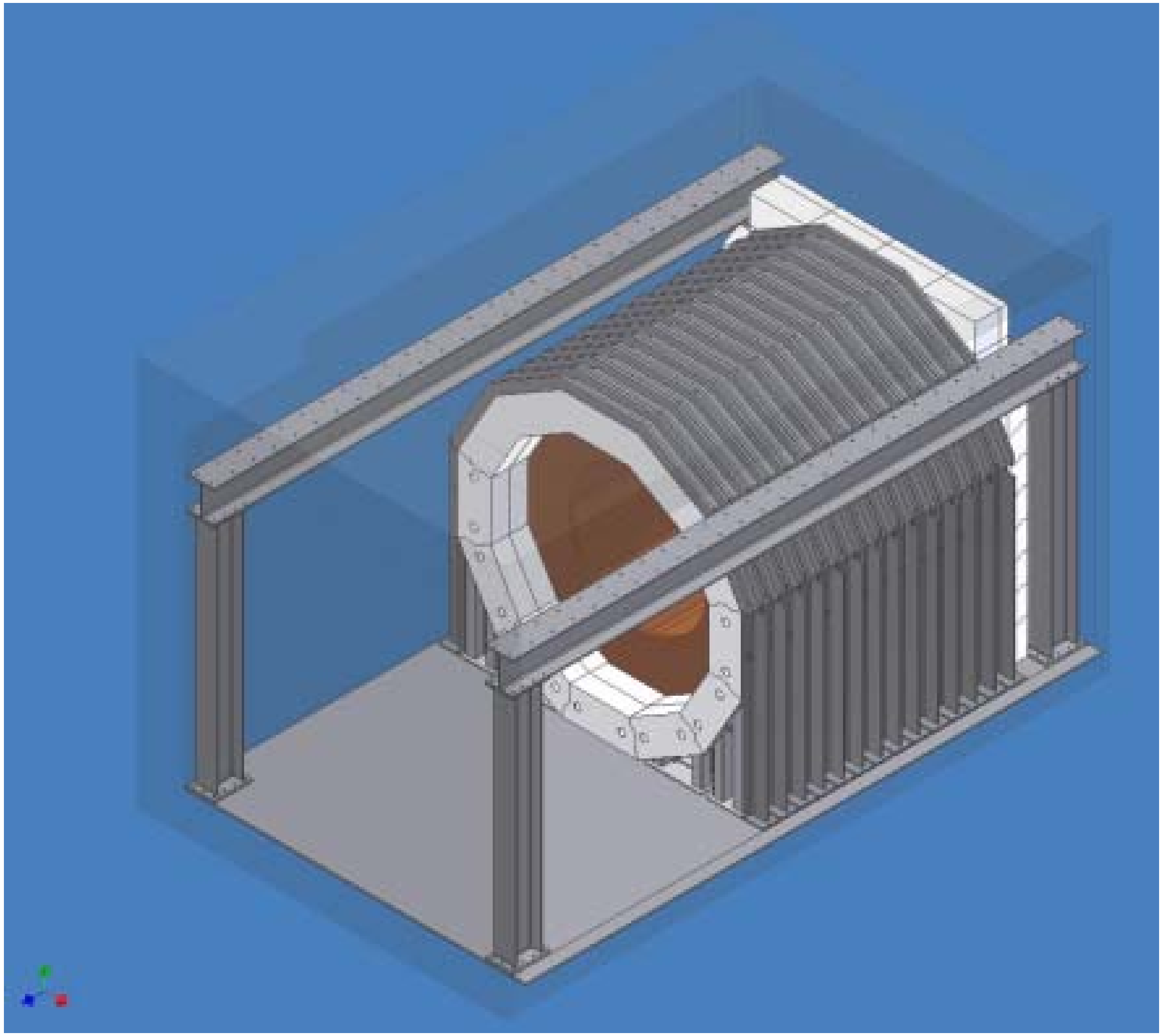
[a] Alabama using MIT reactor
[b] Neuchatel, Alabama
[c] Alabama, Stanford, SLAC, Carleton
[d] Laurentian
[e] Commercial, Canadian Inst. Standards

Cryostat and gantry system views

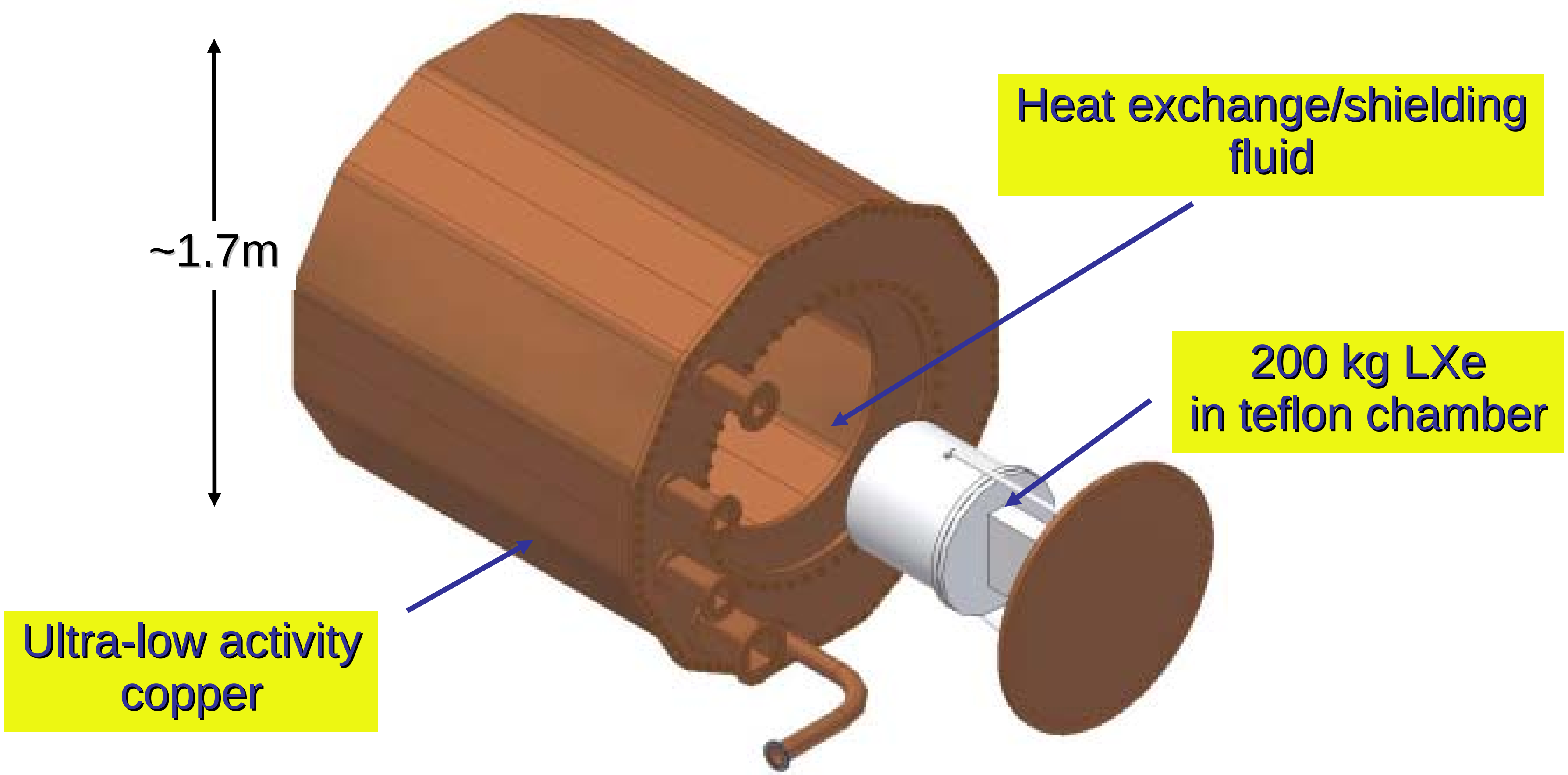








EXO-200: a 200 kg LXe TPC with scintillation readout in a ultra-low background cryostat/shielding



Cryostat being fabricated at SDMS (Grenoble)

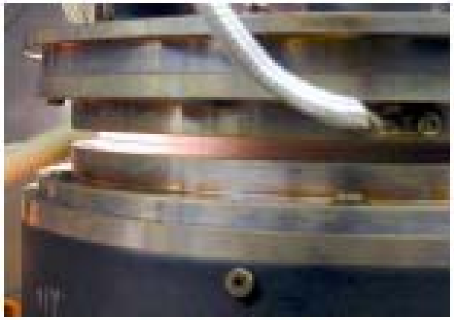
After machining and welding plates are returned to shielded storage

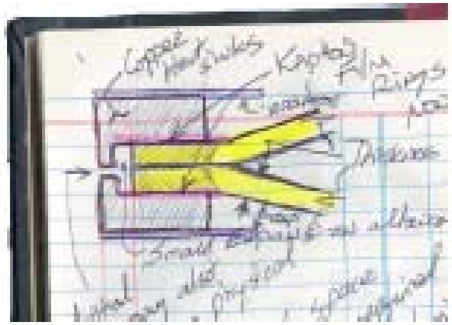
Modular Clean Rooms at Stanford

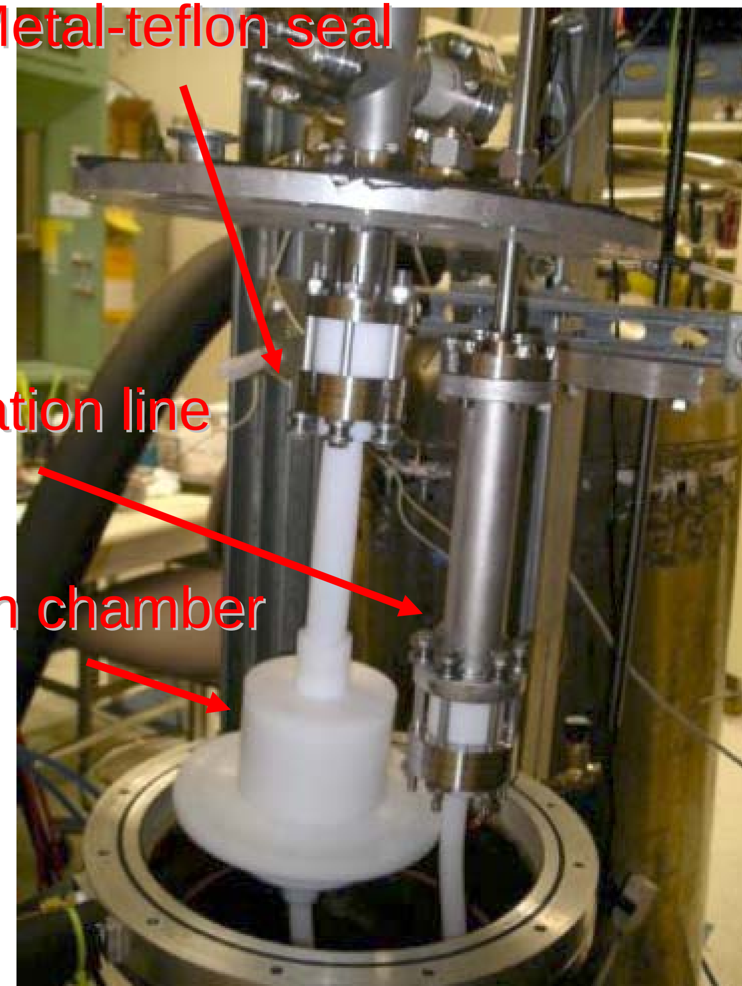
EXO-200 TPC Basics

- Measure both ionization and scintillation light to get best energy resolution
  - Info on event topology important for background separation.
  - Test ability to measure position of decay for Ba^+ extraction in full EXO
- The detector is a cylinder of 44 cm ID by 44 cm inner length.
- The cylinder is split by a cathode plane at the center so there are two symmetric drift regions. The cathode runs at negative HV.
  - Max HV is ~ 70kV (~3.5 kV/cm drift). Energy resolution improves with drift field, but there are arguments that separation of 1 vs. 2 primary electrons might be better at lower fields.
    → field optimization is an important mission of EXO-200
- Readout "style":
  - Crossed wires, 100μm wires, 3mm pitch, ganged in groups of 3 (48ch. x, 48ch. y), total 96 ch. per 1/2 detector
  - APDs for scintillation readout

Teflon chamber R&D

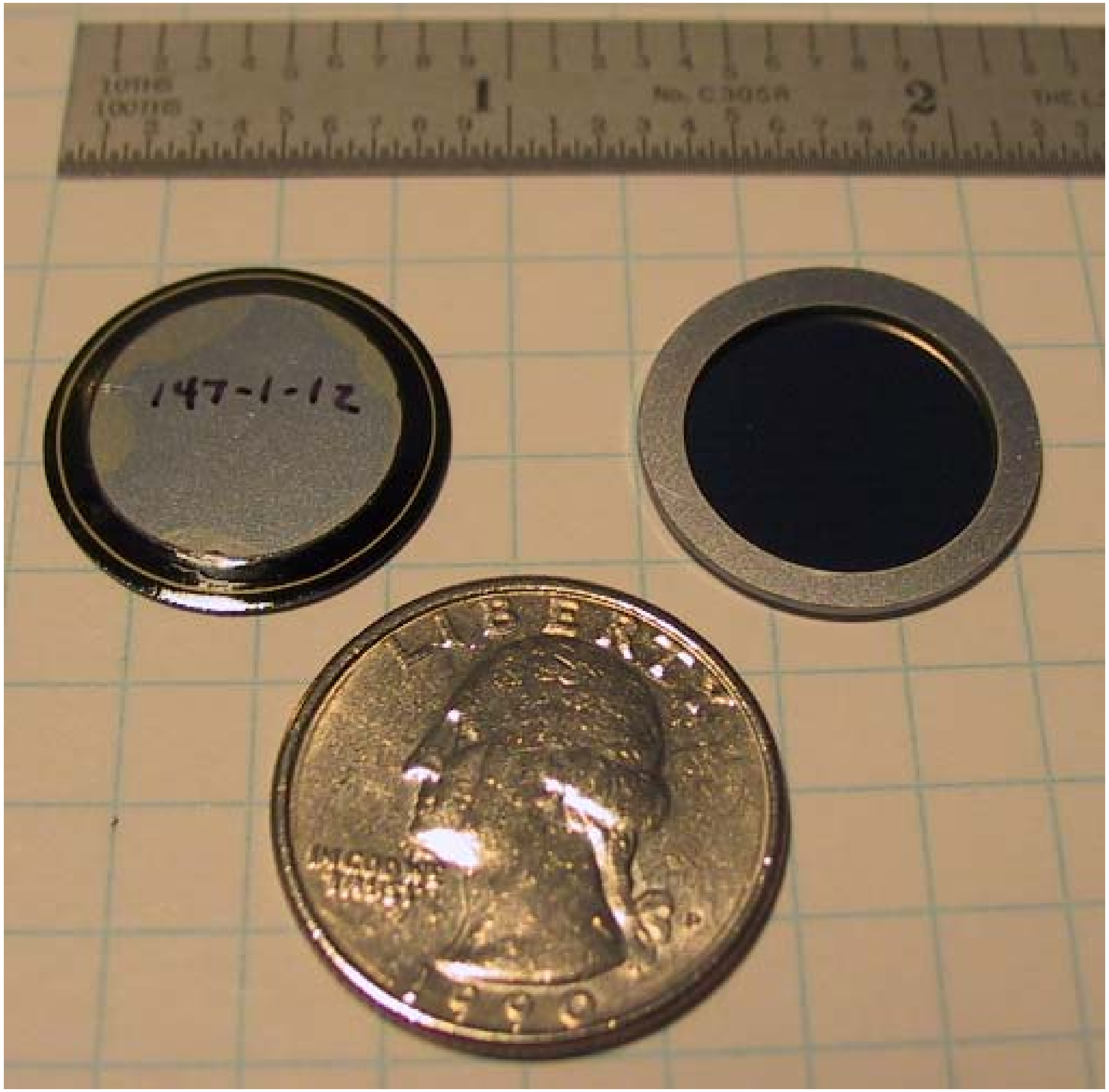






Unmounted LAAPD from Advanced Photonix

Special gold-less production for EXO-200



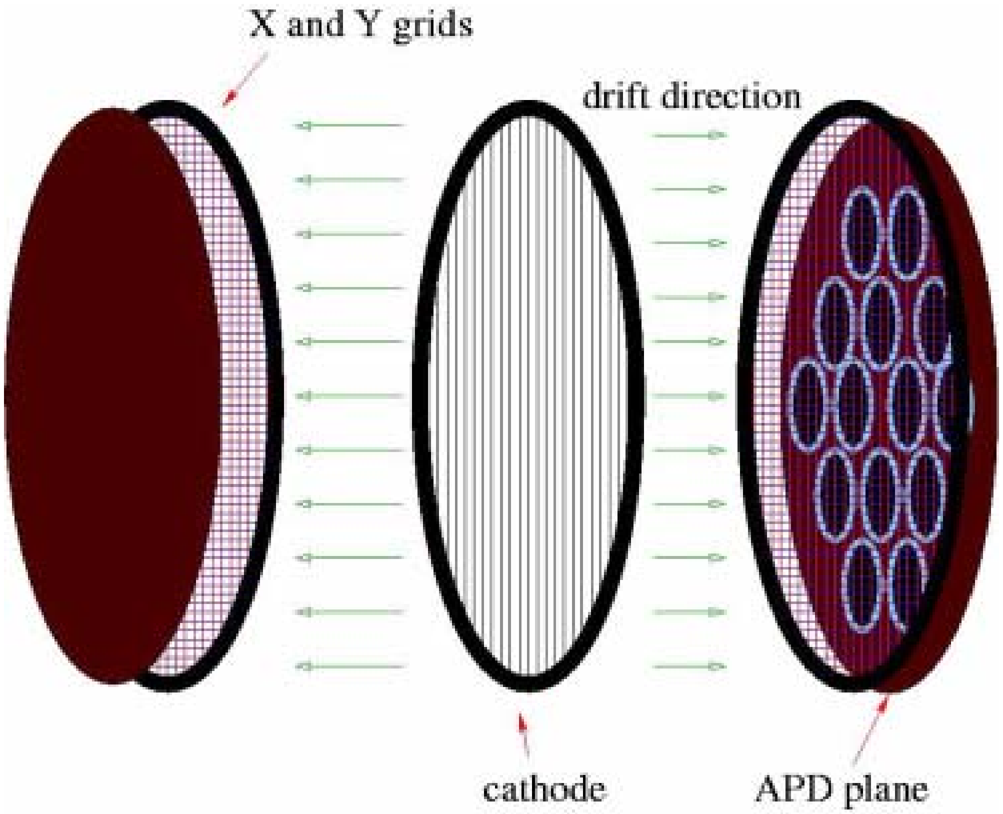
APDs are ideal for our application:
- very clean & light-weight,
- very sensitive to VUV

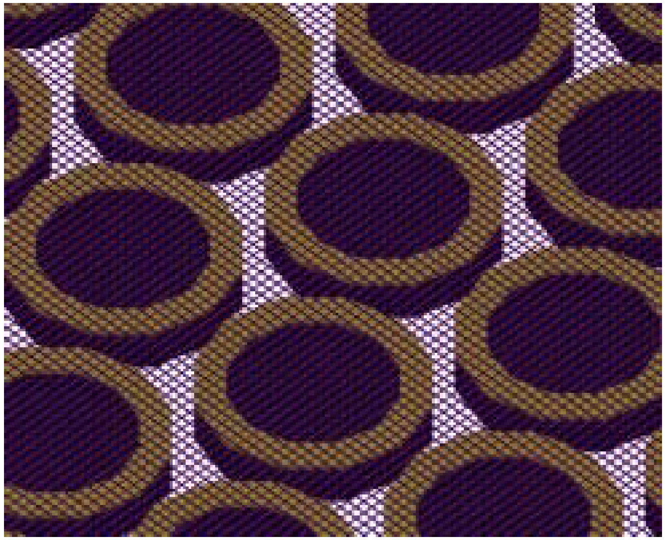
QE > 1 at 175nm

Gain ~ 100-150
V ~ 1500V
$\Delta V < \pm 0.5V$
$\Delta T < \pm 1K$ APD is the driver for temperature stability
Leakage current OK cold

Channel count: 2×300

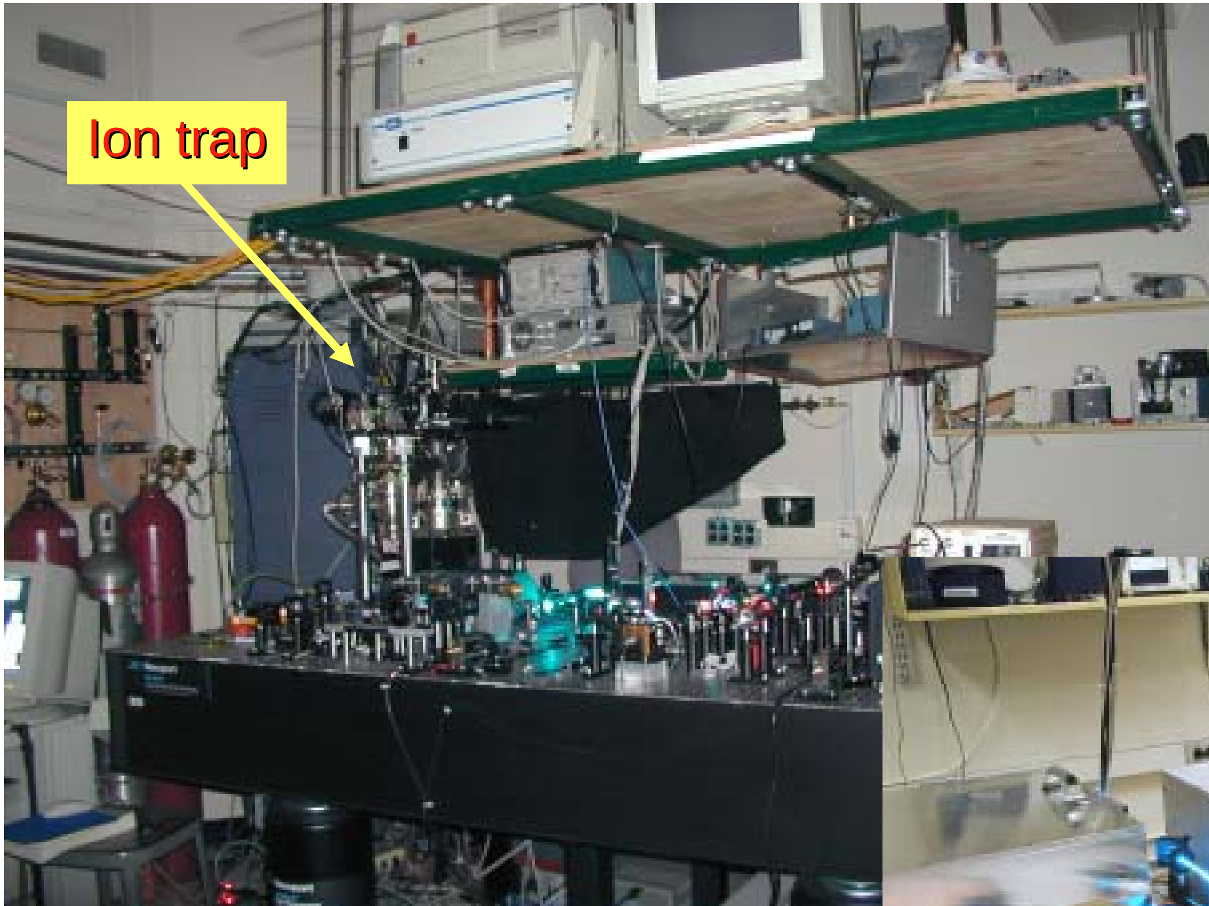
Mounted APD Layout

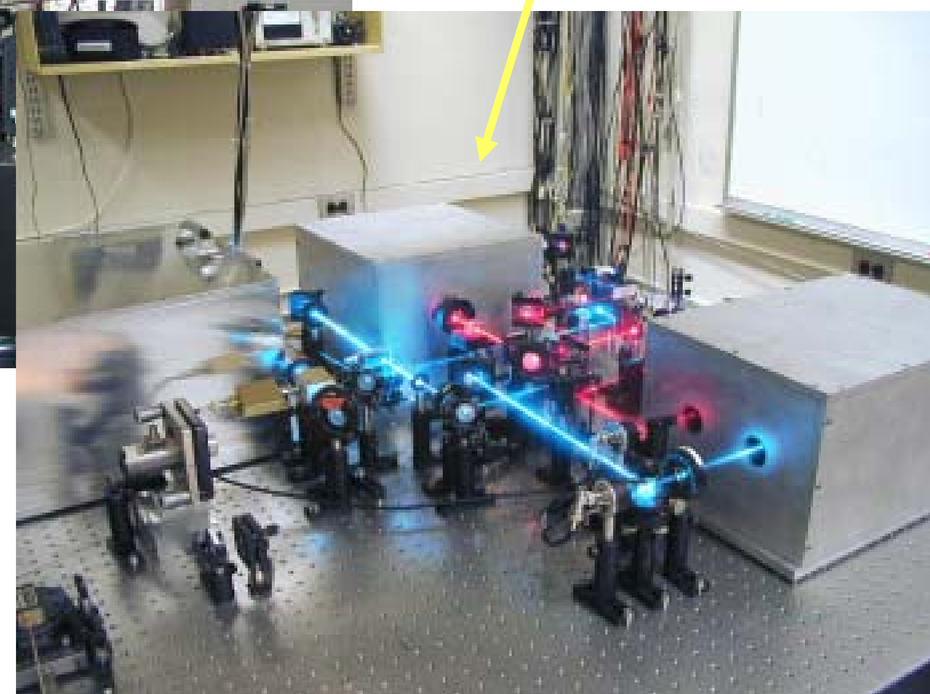




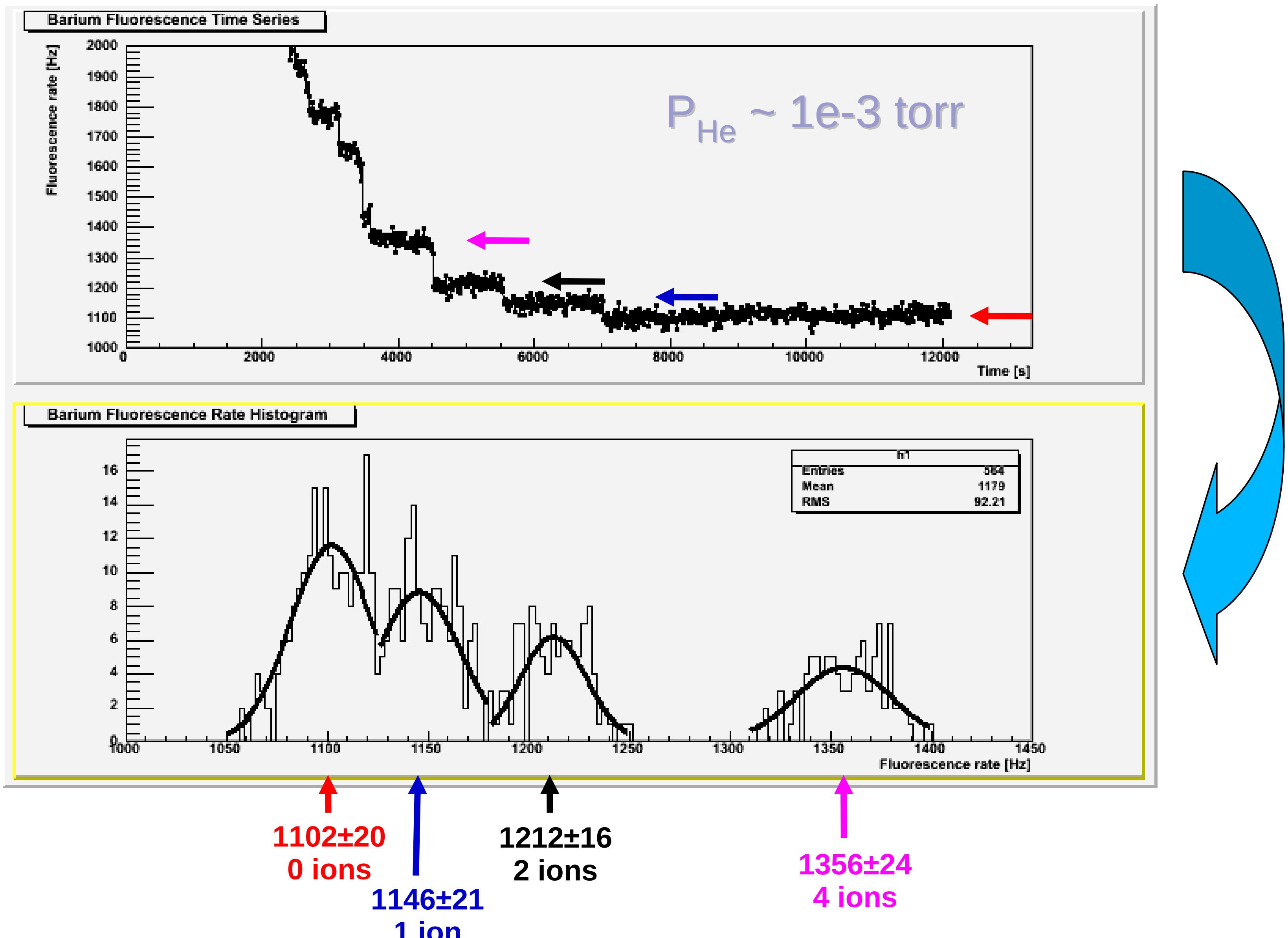
Ba^+ Grabbing & Tagging R&D

Single atom spectroscopy at Stanford and Colorado State

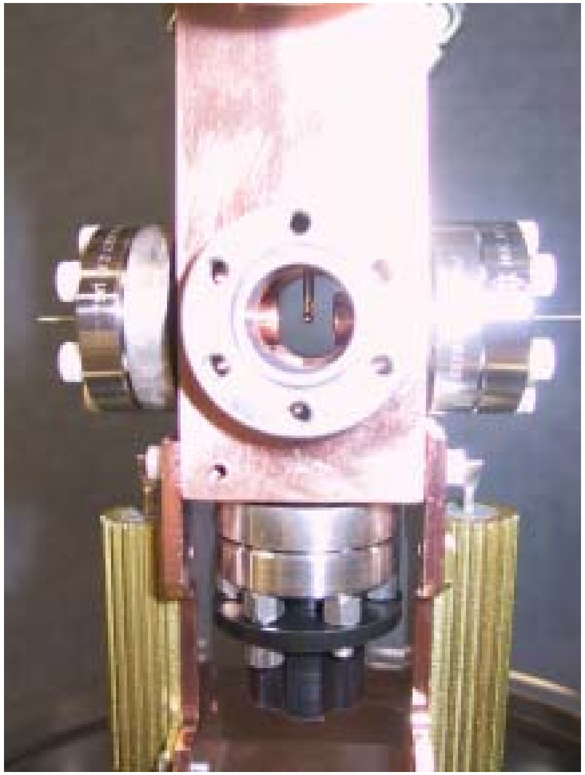


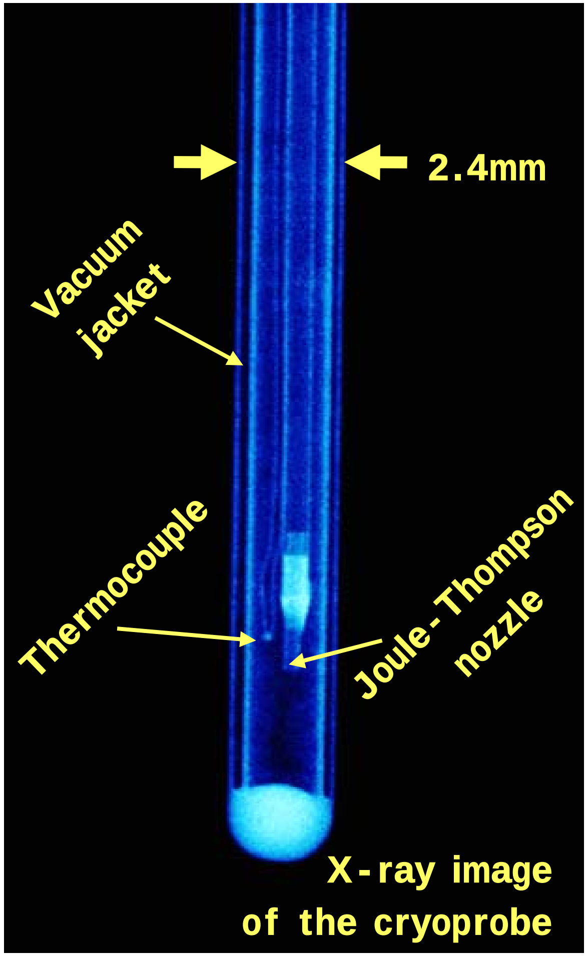


Single-ion detection in presence of He background gas



Initial R&D on grabbing/release uses ^{230}U source and α-counting at SLAC





Ba grabbing and tagging R&D

- Good quality tagging in presence of some Xe/He gas
- He stabilization of Xe-induced unloading
- High efficiency trap-loading scheme (linear trap)
- Linear trap construction close to final device
- Single Ba ion source development

Ba tagging

- Experience grabbing on Xe-ice and metal tips
- Field emission release from STM tip, further cryotip developments

Ba grabbing

Done
In progress

In addition continue R&D on tagging in LXe: very high rewards if successful.

EXO-200 Majorana mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.481MeV endpoint
5) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr R.Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	Majorana mass (eV) QRPA	NSM
Prototype	0.2	70	2	1.6*	40	$6.4 \cdot 10^{25}$	0.27†	0.38♦

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5} \cdot 10^{25}$, $\pm 3\sigma$ range (0.24eV – 0.58eV)
(Phys. Lett. B 586 (2004) 198-212)

In 200kg EXO, 2yr:

- **Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd → 2σ**
- **Best case (NSM, lower limit) 162 events with 40 bkgd → 8.5σ**

EXO Majorana mass sensitivity

Assumptions:

1) 80% enrichment in ^{136}Xe
2) Intrinsic low background + Ba^{+} tagging eliminate all radioactive background
3) Energy resolution only used to separate the 0ν from 2ν modes:
   Select 0ν events in a $\pm 2\sigma$ interval centered around the 2.481 MeV endpoint
4) Use for $2\nu\beta\beta$ $T_{1/2} > 1 \cdot 10^{22}$ yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	2×10^{27}	50	68
Aggressive	10	70	10	1†	0.7 (use 1)	4.1×10^{28}	11	15

* $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B (68) (2003) 054201

† $\sigma(E)/E$ = 1.0% considered as an aggressive but realistic guess with large light collection area

‡ Rodin et al Phys Rev C 68 (2003) 044302

Courier et al. Nucl Phys A 654 (1999) 973c